# EXPERIMENTAL PROOFS OF THE EARTH'S ROTATION.

WILLIAM F. RIGGE.

In establishing the truth of the Copernican system, professors of astronomy are apt to look upon Foucault's pendulum as the one experimental proof of the earth's diurnal rotation. They may also possibly refer to the gyroscope, to the deviation of projectiles and of bodies falling from a great height, and to trade winds and ocean currents; but if they do, it is rather by way of confirmation than of genuine proof. As leisure and means are wanting for special research, they may settle down to the conviction that Foucault's pendulum is the only true experimental proof that has ever been advanced.

The writer hastens to admit that he had always shared this conviction with his colleagues until about a year ago, when he received from his former director at the Georgetown College Observatory, Father Hagen, what is officially called Volume I, No. 1, New Series, of the Publications of the Vatican Observatory. It is entitled "La Rotation de la Terre, Ses Preuves Mécaniques Anciennes et Nouvelles, par J. G. Hagen, S. J., redigé en Francais par P. De Vregille, S. J." It contains a wealth of information upon the subject, together with two new and original proofs, which it has long been the intention of the writer to present in an abridged and popular form to the readers of this magazine.

The author begins by stating that all experimental proofs of whatever kind are based upon three fundamental principles, the motion of the centre of gravity, the constancy of areas, and *vis viva*, although all these three are ultimately reducible to the one of inertia. Under the first he classes Foucault's pendulum and the horizontal movement of projectiles. Under the second are all motions of projectiles and falling bodies, and notably the bent spring of Poinsot and the isotomeograph. The third comprise all complicated instruments, such as the compound pendulum and the gyroscope.

There are also three degrees of perfection in the experiments, inasmuch as they prove the earth's rotation qualitatively, quantitatively and with precision. For example, an experiment with Foucault's pendulum would be a qualitative proof, if the plane of the pendulum should appear to turn in the proper direction. It would be a quantitative proof, if it turned through the proper angle in the given time within the small percentage of error generally allowed in practice. It would

be a proof of precision, if the fact corresponded perfectly with the theory. Such a proof of precision, the author says, is to be found only in the method of Kamerlingh Onnes.

The chronological order, which is given together with the bibliography of the subject, is divided into five periods; the prehistoric, in which nothing of scientific value was actually accomplished, that of the fall of bodies, of the simple pendulum, of more perfect apparatus, and finally the modern period.

## I. Falling Bodies.

1. *Free Fall.* If the earth turns on an axis, every point on it and in it moves in a circle, whose center is in this axis at the foot of the perpendicular dropped to it from the given point. The angular velocities of all points are necessarily the same, but their linear velocities are directly proportional to their distances from the axis. For this reason bodies on the top of a tower move eastward with greater speed than those at the bottom. The actual rotation of the earth is therefore proved by experiment qualitatively, if we can show that this difference of velocity exists and is in the proper direction. It is proved quantitatively, if we can measure its amount. The simplest method of doing this is to drop a body from a height and establish its eastward deviation.

One of the very first experimental efforts made to establish the earth's diurnal rotation was suggested by Mersenne about the year 1644 near Paris. It consisted in firing projectiles from cannons pointed towards the zenith. It was thought that the shots would fall in a definite direction. But they fell in all directions and to different distance. Similar failures met the experiments at Strassburg in 1770 and at Toulouse in 1851.

Guglielmini at Bologna in 1790 was the first to experiment with bodies falling from a height. He used lead balls accurately turned and polished. He suspended each one in turn by a thread attached to that point of the ball which was on top when it was floated in mercury. He cut the thread with a knife and allowed the ball to fall 90 feet. Unfortunately it was only after six months that he suspended a plumb line at the place in order to find the deviation of the balls from the vertical. He neither tells us from what point of the compass the threads were cut, nor the bearing of the sides of the tower.

Benzenberg repeated these experiments at Hamburg in 1802, using generally a fall of 235 feet. He observed during the day time, while his predecessor had worked after midnight. But he took the precaution to suspend his plumb line immediately before and after each set of falls, and to cut the thread half of the time from the north and the

other half from the south. The meridian line was found by means of a compass needle. The balls were an alloy of lead and zinc. As the extreme deviations of his balls from the vertical are nine times the mean distance of all and, as according to his own statement, the sun, coming out of the clouds at noon, upon one occasion, warmed the south side of his wooden tower so much as to throw his plumb line 1.5 lines towards the north, Benzenberg's results, like those of Guglielmini, cannot be considered to offer even a qualitative proof of the earth's rotation.

Benzenberg also dropped 40 balls in a mine at Schlebusch from a height of 262 Paris feet, but gives the results of only 28 of these. Gilbert says that neither of these two attempts of Benzenberg's have any scientific value. A more lenient judge, however, may find in his second one some general eastern tendency.

Reich experimented with a fall of 158.5 meters in a mine shaft at Freiberg in Saxony in 1831. He used two methods of suspending his balls. The first was to hold them with tongs or pincers, one jaw of which opened alternately to the north and to the south. The second was to heat them in boiling water and place them on a ring, through which they fell as they cooled and contracted. He also turned the tongs and the ring halfway round during each set of falls. His balls were made of tin, lead and even ivory, but most were of an alloy of tin, bismuth and lead. The theoretical value being 27.5 mm, he obtained a mean easterly deviation of 28.4 mm, an excellent result. His mean southerly deviation of 1.5 mm is sufficiently small in view of his experimental errors not to weaken in any way the theory of Gauss and Laplace, according to whom the meridional deviation is sensibly zero.

Hall in Cambridge, Mass., preferred the conveniences of a laboratory and the moderate height of 23 meters to the towers and deep shafts of his predecessors. His experiments took place between April 26 and July 25, 1902. He suspended his balls by a thread below a ring, pressing the ring down on them by a lever and counterpoise, and then burned the thread with a gas flame. Instead of letting the balls drop on a block of hard wood, as had been done heretofore, he caught them in a plate full of a mixture of soap, lard and wax. In turning the plate about its center, he could gather six balls into the corners of a regular hexagon. He recorded 948 falls.

He found an evident easterly deviation, the probable error of his determinations being less than the observed value. He attributed to his results only a feeble quantitative signification. His southerly deviation cannot be considered to be certain.

Hooke's trials before the Royal Society in London in 1680 have only an historic value. He affirmed that the fall of a heavy body would be more to the south than to the east. As the height used was only 27

feet and the theoretical easterly deviation less than half a millimeter, Gilbert declares him to have been under an illusion. Similar judgment must be meted out to other minor experimenters, whose names and results are scarcely worth mentioning.

It is, however, of interest to note some of the suggestions made in regard to the places and manner of experimenting with falling bodies. Laplace proposes the national observatory of Paris, where a height of 54 meters would give a theoretical easterly deviation of about 6 millimeters. Benzenberg in 1804 pointed to the Pantheon in Paris and to St. Peter's in Rome as ideal spots for such investigations, little dreaming that both places, at intervals of half a century, would furnish different and new proofs of the earth's diurnal rotation. Oersted, in writing to Sir John Herschel in 1846, calls upon the British Association to make these experiments. Gilbert says that there are not a few mine shafts of 300 meters for this work. Cajori in 1901 suggests the Washington Monument with its interior height of 165 meters.

2. *Impeded Fall.* It seems to have been a foregone conclusion that the greater the fall, the more accurate the results would be. Hall in 1902 was the first to content himself with the moderate height of only 23 meters, after having developed a scheme for the Washington Monument, and not having been allowed by the War Department to put it into execution. A reduction of the height does away with the influences injurious to the body's velocity, its rotation, and the resistance of the air. In fact even a modified Atwood's machine, which, as we know, diminishes the velocity of a falling body to any desirable extent, gives measurable results, as Father Hagen himself proved in 1911. In his later experiments the pulley was fixed, as it always is in Atwood's machine. This did away with two theoretical advantages, which a suspended pulley would have. It prevented the observation of the deviation of the rising counterpoise, as well as the reversibility of the experiment. These theoretical losses were, however, more than offset by the practical advantage of stability, with which neither unifilar nor bifilar suspension could compete.

A fall of 23 meters was used in the experiments. The weight was only 50 grams, while its counterpoise was three-fourths as heavy. The weight fell through an air-tight cylinder, at the bottom of which were two small windows, one on the north and the other on the east side, while the counterpoise ascended on the outside of the cylinder. The fall occupied ten or eleven seconds. As the counterpoise reached the top, its velocity was checked by its picking up a metallic plate, which was then held fast by a spring. As the weight also was thereby arrested and prevented from further falling, any deviation it had experienced would betray itself in a pendular swing, whose double ampli-

tude could be observed by a telescope. At every trial the first direction of this swing was invariably towards the east, and its extent was always noted the moment before the weight had ceased to fall. The mean of 66 easterly deviations was found to be 0.90 mm, 0.01 mm more than its theoretical value, with a probable error of 0.03. The mean of 22 southerly deviations was 0.01 mm, the probable error being nearly three times as great, so that these experiments lent no support to the persistent claim, which seems to be all but universal, that a southerly deviation must exist. This much-discussed meridional deviation of a falling body is nothing but the effect of the earth's centrifugal force, which has driven its surface fluids towards the equator and made the equatorial diameter about 26 miles longer than the polar. While the existence of this force is universally admitted, it has, however, never met with an experimental proof. Laplace and Gauss declared it to be practically insensible, and Bertram says that in latitude 45 degrees with a ten second fall it would not be more than the one-hundredth of a millimeter.

Puiseux's suggestion of two basins of mercury at different heights was tried in 1865 by Abbadie, who could see no measurable difference in the inclinations between one 10 cm below his telescope and another 10.5 meters below. Maillard's experiment is very original and very elegant from a mathematical point of view, although its execution leaves much to be desired. He took a vertical brass tube with an external diameter of 10 cm, and set it upon a glass cylinder 20 cm. long so that a paraffine float 5 or 8 mm in diameter might be observed near the bottom, when the water was allowed to run out of the tube. As this was done by means of two orifices one north and the other south, or one east and the other west, it was thought that an easterly and a southern deviation of the float might be observed. The results were, however, masked by too many practical difficulties.

## II. The Pendulum.

When a pendulum is allowed to swing, we know that it does so under the influence of gravity alone and that this force acts in a vertical plane without any horizontal component. The plane in which the pendulum vibrates must therefore remain the same, and if it changes at all, the change must be only an apparent one and due to the real turning of the floor beneath it, the turning of the ground, and the turning of the whole earth. When a pendulum is swung in the northern hemisphere, the ground to the south of it moves eastward faster than the point beneath it, while the ground to the north moves with less eastern speed and relatively, therefore, to the west. The consequence is a turning of the ground to the left as seen from underneath the

pendulum, but as this is not evident to the eye, since all bodies and ourselves included are involved in it, the plane of the pendulum appears to turn to the right with a speed which varies inversely as the sine of the latitude.

Three kinds of pendulums have been used to prove the rotation of the earth. The first is called the simple pendulum, because it approaches to some extent to the usual physical definition of this instrument. When it swings in an approximately vertical plane, it is called a Foucault pendulum. When it swings in a nearly circular curve, it is a conical or Bravais pendulum.

The second kind of pendulum swings in a horizontal plane, and is called a Hengler pendulum.

The third kind, the compound pendulum, has so many varieties that it bears no particular name.

The ball of a Foucault pendulum is very much like a projectile thrown horizontally, which in virtue of its inertion deviates to the right, as Foucault himself remarked. While falling bodies can at best furnish only a qualitative proof of the earth's rotation, the pendulum may be made to give a quantitative one, indeed one experimenter has even succeeded in getting a proof of precision.

1. *The Foucault Pendulum.* The apparent change of the plane of vibration of an ordinary pendulum had been observed by Viviani in Florence in 1661, two centuries before it had found an explanation. And by a strange opposition of facts, Foucault developed the theory of this deviation, before he had made any experiment whatever. If he or Newton had known of Viviani's discovery, they would surely have found in it at least a qualitative proof of the earth's rotation.

Foucault's first experiment was made on Wednesday, January 8, 1851, at two o'clock in the morning, with a thread only two meters long and a ball of five kilograms in weight, hung from the vault of a cave, the amplitude of the vibrations being from fifteen to twenty degrees. He next used a thread eleven meters long, and finally, at the request of the prince president, Louis Napoleon, he performed the world-famed experiment in the Pantheon with a steel wire 1.4 mm in diameter and 67 meters long and a weight of 28 kilograms, the horizontal swing covering an extent of six meters. The upper end of the wire, instead of being directly attached or soldered, passed loosely through a draw plate set into the vertical slot of a steel plate. The horizontal deviation was one degree in five minutes or 2.3 mm at each vibration, as he had predicted, and it swung for about five or six hours.

As Foucault had suspended his pendulum in Paris in latitude 48° 51′, Lamprey's trial at Colombo in Ceylon, in latitude 6° 56′, offered a good verification of Foucault's law of sines. The mean of eleven observa-

tions gave a result differing three per cent from the theoretical value. If two observations made in the N.W. and S.E. direction are rejected, the agreement between fact and theory is perfect.

During the same year 1851 a Foucault pendulum was swung in Rio de Janeiro in the southern hemisphere, in which the deviation was in the opposite direction to that at Paris and Colombo. The weight was a hollow sphere of 10.5 kilograms, the thread was of linen without torsion, and the pendulum 4.365 meters long. It was found that between the plane of the meridian and that of the parallel of latitude, there were two invariable planes of oscillation in which there was no deviation. The report states that in half an hour the deviation was 5° 9′ towards the east in the meridian, and 5° 12′ towards the south in the parallel plane. The writer evidently intended these figures to mean hourly variations, since they are double the theoretical values for half an hour. The direction of the deviation is also ambiguously given, his words being "in the sense of the earth's rotation", which when taken literally would show that the deviation had always been in the wrong direction. It is an astonishing fact that no experiment of any scientific value has even been reported from the southern hemisphere.

Several observations seem to prove that the deviation was different in different azimuths. Thus at Oxford, where iron and lead weights of twelve pounds and a piano wire of 80 feet were used, the deviation was noticed to be accelerated as the plane of vibration approached the magnetic meridian, and to be retarded when it was at right angles to it. The coming and going of visitors also affected the results. It is very remarkable that steel wires proved to be more unmanageable than those of soft iron.

Secchi's experiments in Rome in 1851 developed an unexpected irregularity. His pendulum was 31.89 meters long and weighed about 28.5 kilograms. He used a soft iron wire 1.8 mm thick, and steel wires of 0.65 and 1.3 mm. The first gave the better results. An elliptic motion of the pendulum, which invariably began to show itself after an hour and a half, always took place in the same direction, which was that of the earth's rotation, thereby diminishing the angle of deviation. This peculiar phenomenon was attested to by many witnesses. Many, and Secchi himself, thought it was due, at least partially, to the initial velocity of the weight imparted to it by the rotation of the earth itself. The rigidity of the wire might also be a cause of it. Airy suggested an oval shape for the hole through which the wire passed, and an unequal taper of the wire. With a major axis, that is, a horizontal amplitude of one meter, the greatest minor axis of the ellipse observed was 20 mm. Secchi's results differed one-fifth of one per cent from their

theoretical value. He found no difference between vibrations executed in the meridian and in the prime vertical.

Garthe, in 1852, in the cathedral at Cologne, was the first to use a Cardan suspension. As its movable ring had a diameter of only 5 cm, while his pendulum was 50 meters long and weighed 17 kilograms, it introduced no sensible error. Nearly a thousand visitors came to see the experiments. The error was one-sixth of one per cent. Garthe does not mention any elliptic motion, although two oscillations extended over three hours fifty-two minutes, and the deviation amounted to 45 degrees. Nor does he speak of the Cardan suspensions whose two pairs of steel axes were not in the same plane.

Bunt in Bristol, instead of drawing the weight aside and securing it by a thread and then burning the thread, as all his predecessors had done, let it go by hand and tried by a side touch to give it an elliptic motion opposite to that he had last observed. After applying all the necessary corrections, he obtained a value correct to one per cent. Van der Willigen in Harlem in 1868 followed Bunt's method, his percent of error being 0.5.

2. *The Bravais Pendulum.* Bravais hung up a conical pendulum 10 meters long, in the large meridian room of the Paris Observatory. The weight was a copper cylinder full of mercury and weighed 10.5 kilograms. Below the pendulum was a space of about one and a half meters. This was occupied by a kind of clockwork which had one shaft set up vertically, directly under the point of support of the pendulum. A graduated bar extended at right angles to this shaft, and when the clockwork had been set in motion, it pushed the pendulum weight around in a circle. When the centrifugal force generated had swung the weight the desirable distance from the centre, the bar was arrested and then lowered, so as to be out of the way of the weight. The bar could be raised at any time and the distance of the weight from the centre measured in any direction, so that the exact shape of its trajectory could be determined.

The Bravais differs from the Foucault pendulum in this, that in it the deviation in azimuth cannot be observed, but there is instead a change in the time of a vibration. As a variation of space appeals more to our senses than one of time, the Bravais pendulum never met with popular favor, and seems to have been set up only once and that by the inventor himself. It has, however, two points of superiority over the Foucault pendulum, in that it is reversible, since it may be given a dextrorsal as well as a sinistrorsal revolution, and in that the time of a revolution or of a vibration may be lengthened or shortened at pleasure.

On account of the reversibility of his pendulum, Bravais was enabled to experiment with only one pendulum as well as with two

revolving simultaneously in opposite directions. In the first case he observed the time of vibration at a distance by means of a telescope, and then repeated the experiment with the motion reversed but with the same starting amplitude. In the second case he used two pendulums of 10.2 and 10.1 meters in length, and 0.7 meter apart, and noted the moments when their supporting wires appeared to be coincident in the telescope, once when they crossed the field of view from opposite directions, and again when they seemed to come from the same direction.

The practical difficulties of the Bravais were very similar to those of the Foucault pendulum. There was a noticeable change in the time of vibration in two azimuths at right angles to one another, and the circular trajectory always showed a tendency to degenerate into an elliptical one, the major axis of which always assumed a fixed direction. Bravais investigated these irregularities with great care and computed corrections for them, but he neglected those of the manner of suspension as insignificant. Although his results were of great value quantitatively, and within about four per cent of their theoretical value for a single pendulum and about one per cent for two pendulums, he did not think them sufficiently precise. It may be of interest to add that his ten meter pendulum experienced an acceleration or a retardation in azimuth of 11.43 seconds of arc in each second of time, one revolution occupying about 6.5 seconds.

*To be Continued.*

## THE STORY OF THE ZODIAC.

EDITH R. WILSON.

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When we turn to the examination of Egyptian planispheres, we are met by a most perplexing variety of stellar forms which at first sight quite escape our recognition. Each Sign and Constellation appears, portrayed not only under its stellar but also under its mythical attributes which are distinctly Egyptian, while the whole astral company go sailing along the Ecliptic in boats, space being regarded, by our friends of the Nile, as a great abyss and the term, "Dweller in the Abyss," being a generic title for a planet or star. The most famous Egyptian zodiacs known to us are those of the Temple of Hathor at Denderah,—comprising the so-called "square" and "round" zodiacs,—and that of

at which the other types begin to predominate. From the material at hand, however, there seems to be no satisfactory method of obtaining these values.

In regard to the spectrographic exposures on the Milky Way it should be stated that every precaution was taken to prevent sunlight from any source reaching the plate. The exposures were not begun until the sky was thoroughly dark and were closed before dawn. Furthermore, no exposure was made while the moon was above the horizon.

If the result as given above should be found to be general it will have a bearing on cosmogonal theories but it must necessarily be accepted with some reserve until confirmed by additional work with a spectrograph of higher dispersion.

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3. *The Compound Pendulum.* Strictly speaking the Foucault and Bravais pendulums are compound, but as they approximate to the definition of a simple pendulum more closely than those that remain to be mentioned, they deserve to be in a class by themselves. By a compound pendulum is here meant one that renders the diurnal rotation more evident, or keeps the time and amplitude of a pendulum constant, or increases the accuracy of the observation.

Franchot seems to have been the first to maintain the oscillations of a Foucault pendulum by means of an electromagnet. Garthe, who was the first to use a Cardan suspension, as mentioned before, also describes a clockwork contrivance due to Kabisch, which turned on two vertical steel pivots, and carried an index moving over a dial placed horizontally below the lower pivot. As the plane of vibration changed, it carried the clockwork with it, and indicated the angle on the dial. The instrument showed an hourly deviation of 10°.6 instead of 11°.7, a remarkable result in view of the enormous friction it entailed.

Porro suspended a short pendulum in a vacuum, attached a prism near the point of suspension, and observed the deviation and the axes of the elliptical trajectory with a telescope.

Foucault took up and perfected Franchot's electromagnetic contrivance to the extent that he made it absolutely independent of the pendulum itself, and exhibited it at the Universal Exposition in Paris in 1855. A single electromagnet was placed vertically under the lowest point of the pendulum. When the ball, which was of soft iron, was at the extremity of its swing, the circuit was closed and the ball attracted. As this attraction was mutual, the electromagnet was raised when the ball was nearest, and the circuit opened. The electromagnet fell back into place by the time the ball was at the other extremity of its swing, and thereby again closed the circuit. The vibrations could thus be kept up indefinitely and the deviation made very apparent.

Strange to say, this idea was expressed 70 years earlier by Poinsinet de Sivry, who proposed to make a mariner's compass without a magnet by maintaining the oscillations of a pendulum over a horizontal dial, by intermittent puffs of air. As the pendulum would keep its plane of vibration unaltered, it would show a change of azimuth exactly like a magnetic needle. Foucault, however, had the genius to use the whole earth as his ship.

Bernardi in Vicence in 1868 applied clockwork which kept the oscillations of the pendulum rigorously rectilinear. In 16.75 hours it showed a deviation of 190°.5, instead of the theoretical 179°.3.

Kamerlingh Onnes in 1879 made use of the suggestions of Porro and Gauss with notable improvements. His Cardan suspension carried a movable central part entirely devoid of knife edges. A beam of light was twice totally reflected from two prisms. He considers the Foucault and Bravais pendulums as two extreme forms of a spherical pendulum, and their elliptical perturbations as particular cases of the trajectory described by a mass that is not perfectly symmetrical in respect to its vertical axis. These trajectories are only modified forms of Lissajous curves, produced by the combination of two unequal pendular movements at right angles to one another. The experiments of Kamerlingh Onnes are the only ones in Father Hagen's estimation to merit the name of proofs of precision. His assistant, Father Stein, therefore devotes a special appendix of 72 pages to their mathematical discussion.

Two demonstration pendulums, which cast a beam of light on a screen, are worth mentioning. In Edelmann's form the weight is magnetized as a whole or in part and in its deviation continually directs a small piece of soft iron, which is supported below it and is furnished with a mirror. Berget's pendulum is a bronze rod one meter long carrying a copper weight of two kilograms. The deviations are read by a microscope or projected on a screen.

4. *The Hengler Pendulum.*—The horizontal pendulum was invented three times; by Hengler in 1832, Perrot in 1862, and Zöllner in 1869, all these inventions being independent of one another.

Hengler gives only a few details concerning his pendulum. He says that it extended in an east-and-west direction and that from its extremity a weight hung by a thread which could be lengthened to nearly a hundred feet. When the weight was raised, the arm of the pendulum is said to have swung towards the south. This is a qualitative result. Quantitatively he says that an elevation of the weight of only a few feet caused a noticeable deviation of the pendulum. These meager details deprive the experiment of all value. Hengler does not even give its theory.

Four years later Guyot performed a new experiment in the Pantheon in Paris in 1836. Knowing that a falling body deviates toward the east, he thought that a long plumb line should do the same. He therefore took a thread 57 meters long and attached two little balls to it, one near the top and the other near the bottom, and looked at their images in a basin of mercury placed underneath. He saw what he expected; the lower ball was 4-1/3 millimeters east of the upper one. Although Arago did not favor Guyot's work, he fell into the same theoretical error. He said that if two pendulums were set up east-and west of one another, one short and the other very long, that the line of the short one when produced would deviate to the east of the long one, not knowing that the centrifugal force on the earth's surface drives bodies towards the equator, that is, along the meridian. He does not even seem to have studied the theories of Gauss and Laplace, since he maintains that a falling body deviates to the east-southeast.

## III. The Gyroscope.

The gyroscope, as used for our present purpose, consists essentially of a symmetrical torus, one point at least of whose axis of symmetry is fixed to earth, so that on account of its inertia and rapid rotation, it may show any displacement of its point of support and especially the diurnal revolution of the earth. A gyroscope is free, if it can turn through all three directions in space. It is constrained, if it can move in two directions only. A torus confined to turn in only one direction, cannot be called a gyroscope, because it cannot, as its name implies, show the motion of its point of support. Foucault was the first to use the word for a machine of his own invention.

The free and constrained gyroscopes behave very differently in the way in which they show the rotation of the earth. The former remains at rest independently of it, while the latter combines two rotational motions into one resultant. For this reason the constrained gyroscope is reversible, while the free one is not. Its theory, however, is very much more complicated.

A free gyroscope may also be called a universal one. A perfect machine of this kind is a mechanical impossibility; and it has therefore

been practically abandoned by experimenters. Among the constrained gyroscopes we class especially the horizontal and vertical types, according as their axes are confined to a horizontal or to a vertical plane. Foucault used all three.

1. *Foucault's Free Gyroscope.* Foucault saw that his pendulum showed only a relative displacement of its plane. He therefore felt himself forced to construct a machine that would keep its plane absolutely unaltered in space. Bohnenberger's apparatus, designed in 1817, seemed to be the best adapted for the purpose, since its torus was free to turn in all three directions, while its center of gravity remained in place. The friction, however, had to be reduced as much as possible. Foucault calls attention to three essential conditions verified in his own apparatus; the axis of the torus must turn with the least possible friction its circular support must be in indifferent equilibrium in any position, and the thread that supports the whole machine must be without torsion. His torus made about one revolution in a second and ran for eight or ten minutes. As the direction of rotation is a matter of indifference, this free gyroscope is not reversible. It is a curious fact that both the instruments designed by Foucault, the simple pendulum and the free gyroscope, are the only ones amongst all that have been used to prove the rotation of the earth, which are not reversible.

Person and Gilbert pointed out the inevitable defects of the free gyroscope, such as friction, want of perfect coincidence of its center of gravity with the intersection of its axes, the torsion of the thread, and especially the fact that when the disk is first set in motion, it is fixed to the earth and must therefore necessarily share its rotation. This impresses a new rotation upon the torus and appears as an imperceptible trembling of its axis.

2. *Foucault's Constrained Gyroscopes.* Foucault himself was quick to see the defects of the free gyroscope, and that this might be converted into a constrained one by fixing one or other of its supporting rings. Arnold in Boston in 1879 placed the plane of his torus perpendicular to the terrestrial equator and gave it a speed of twelve turns a minute alternately in opposite directions. It always inclined in the proper direction, as the theory demanded. But when he placed it parallel to the equator, it remained at rest, in whatever sense it was set rotating.

Gilbert reduced the vertical Foucault gyroscope to a much more simple and strong shape. He replaced its exterior ring by a contrivance in the shape of a horse-shoe mounted on a base, so that it would turn with considerable friction about a vertical axis. The interior ring was given a rhomboidal shape, and the knife edges were displaced 90°, so that the axis of the torus was vertical instead of horizontal. Gilbert

thus introduced an essential change into the Foucault instrument by replacing its indifferent equilibrium by a stable one. In experimenting with it, he placed small sliding weights upon the lower end of the rhomboidal frame. These weights served to give the axis of the torus a position of equilibrium at a definite inclination. This angle was a maximum in the meridian, and zero in the prime vertical. It increased in low latitudes and vanished at the poles, the very reverse of the Foucault pendulum. Gilbert called his instrument a baro-gyroscope. He also placed two tores upon it, with their axes parallel, and turning in the same sense. The deviation was increased, but its mechanical construction was less satisfactory.

Fleuriais has applied the baro-gyroscope to the sextant as an artificial horizon. The torus has a diameter of less than five cm and weighs less than 175 grams. It is set in rapid rotation by means of air currents, and then placed on the sextant back of the horizon glass, where it looks like a straight horizontal line. Baule has made a long series of observations with this instrument, and states that it is beyond all doubt affected by the rotational movement of the earth.

In order to obtain quantitative results, the speed of rotation of the torus must be known and kept constant. Krüger in 1851 first suggested an electric motor, but Garthe in Cologne in 1852 was the first to use one. He could not observe any effect due to the earth's rotation. He was evidently not in touch with the laws recently formulated by Foucault.

It is a pity that Gilbert did not apply an electric motor to his baro-gyroscope. The stabilizing gyroscope of Schlick, used in reducing the rolling of a ship, resembles the Gilbert instrument, although it was never intended to show the earth's rotation and does not do so.

3. *Föppl's Horizontal Gyroscope.* Foucault's horizontal gyroscope lends itself to simplification even more than his vertical, because both rings and the knife edges may be dispensed with. In his original instrument Föppl kept only the tore and its suspension. But he made the latter trifilar, instead of unifilar, and thereby introduced an exterior force that Foucault had tried to exclude completely. Its simplicity called for an electric motor, and this in turn suggested a double torus. Each torus was 50 cm in diameter and weighed 30 kg. Both were of cast iron, and fastened to the two ends of the horizontal axis of an electro magnet. This magnet was supported by three steel wires, while the wires supplying the current hung down loosely. The oscillations of the apparatus were dampened by four plates turning in oil, whose positions could be determined almost to the tenth of a degree. The number of revolutions in a minute, which ranged from 1500 to 2280, were deduced from the indications of a voltmeter, the trials lasting from

fifteen to thirty minutes. The movable parts of the apparatus were covered by sheet iron to exclude air currents. When the common axis of both tores was placed in the prime vertical, it showed a tendency to approach the meridian according to Foucault's law. As this tendency was resisted by the torsion of the trifilar suspension, the axis could turn over an angle of only 6°.576, or 0°.134 short of its theoretical value, thus giving an error of two per cent.

Garthe's electric gyroscope could also be used as a horizontal instrument. Unfortunately he did not know how to explain its action. His geostrophometer, which was never tried, was merely a vertical paddle wheel kept in motion by jets of water, the whole contrivance being mounted on pivots.

While the vertical gyroscope may serve to stabilize a ship, the horizontal one may replace its compass. The former has nothing to do with the earth's rotation, but the latter may be used as a mechanical demonstration of it. To insure its horizontality, the inventor Anschütz replaces Foucault's filar suspension by a basin of mercury. The rotation is maintained electrically. The instrument is of special service on war ships, where an ordinary steel compass would be subject to much disturbance. It has been tried on English, German and Italian vessels (1909). Poinsinet de Sivry's "compass without a magnet" has thus after more than a century taken practical shape.

## IV. Constant Area Apparatus

The principle, according to which the instruments under this heading are grouped, is that known as the areal law, which requires the radius vector of a moving mass to sweep over equal areas in equal times.

1. *Poinsot's Bent Spring.* Next to that of Foucault's pendulum, Poinsot's idea of the bent spring in 1851 is the most interesting on account of its simplicity, at the same time that it is the least understood and most forgotten of all the ideas proposed. He suggested taking a straight and uniform piece of steel, supporting it at its middle by a thread, and then bending the extremities together in the form of a horseshoe and tying them with a string. When the apparatus is in perfect repose, the string is burned, and the spring straightens out again. It then behaves like a Foucault pendulum.

This simplicity itself seems to have occasioned much misunderstanding. Poinsot himself did not dream that his contrivance was reversible and could be made to turn faster than the earth. He imagined that the vertical plane of his instrument was more persistent than that of a pendulum, whereas it is rather less so. He also thought that the effect might be observed for an unlimited time, whereas the recoil of the spring can last only a few minutes. While Poinsot himself did not well

realize the value of his own idea, we shall see later that the three points mentioned offer some real advantages. Even the great Foucault seems not to have grasped the Poinsot idea perfectly. Certainly Baden Powell did not, nor did Tessan and Bertrand. Jullien, however, and Routh, and Furtwängler did.

2. *Baudrimont and Boillot's Suspended Balls.* Baudrimont in 1851 thought that if a ball was supported on an axis parallel to that of the earth, its inertia would make it independent of the earth's rotation, so that it would appear to rotate in the opposite direction. Boillot, 37 years later, had the same idea, and imagined that a ball hung by a thread must turn like a Foucault pendulum. He also proposed to eliminate all torsion by holding the axis with a magnet. Serpieri performed the experiment with a marble ball suspended by a soft iron wire seven meters long. The apparatus obeyed Foucault's law, but the ball showed no signs of rotation. In spite of this, Serpieri and Baden Powell persisted in their belief in the truth of Baudrimont's idea, and attributed the failure to torsion. Secchi and Chelini exposed its falsity. The reason is simple, because the ball has at the start the motion of the earth, like all other bodies in its neighborhood, and its own inertia keeps this up, so that the difference remains zero and the ball appears to remain at rest. Besides, if the idea were true, it would give us an easy way of getting perpetual motion.

3. *The Liquid Currents of Perrot, Combes and Tumlirz.* The fundamental idea of these experiments is that radial currents in a liquid ought to show a deviation on account of the earth's rotation. As these currents may be made to approach as well as leave the center, the experiment is reversible. In the former case the motion ought to be in the same sense as that of the earth, and in the reverse sense in the latter.

Perrot took a large circular basin full of water, which he allowed to stand for a whole day in order to insure its perfect quietude. Having spread some very light particles of wax along a radial line, he allowed the water to run out of a small orifice in the center. The particles deviated towards the right, as seen from the circumference of the basin, and their path became spiral toward the center. He gives no further particulars.

The inverse experiment of centrifugal currents presents much greater mechanical difficulties. Combes in 1859 suggested a method but never tried it. It was to receive a vertically upward jet of water into the middle of a cylinder, which was open at both ends, lying horizontally, and free to move around an axis coincident with the jet.

Without having any previous knowledge of Perrot's experiment, Tumlirz repeated it 50 years later in Vienna with much greater mechanical facilities. At the bottom of a vertical cylinder he placed a

vertical outlet pipe closed on the top but with holes on the side, so as to induce the outflowing water to take a horizontal direction. For this same purpose he made the water pass between two glass disks 5 cm apart and 140 cm in diameter, the upper one being slightly smaller. At the circumference of these disks the water was colored by small orifices containing methyl violet. The colored ribbons of water were very visible, although the velocity was only 1.11mm a minute. After 24 hours the level of the water had sunk only 17.5 cm. Great care was taken to admit the water in a perfectly vertical direction, and to insure an equal temperature throughout.

To prevent the formation of accidental currents, he allowed the water a long time to attain perfect rest, on one occasion as much as 40 hours. He performed the experiment six times and took photographs of the colored ribbons in the water, a whole day after it had begun to flow, by suspending his camera vertically over the tank. The deviation shown on the plates is notably less than that demanded by theory. While it is in three quadrants on all six plates in the proper direction, in the fourth, quadrant it is always in the wrong one. The cause of this anomaly seems to have escaped the experimenter. For this reason it is hardly possible to credit his results with a quantitative value, and even their qualitative determination may be questioned.

4. *Hagen's Isotomeograph.* Father Hagen concludes his work with the discussion of two instruments of his own invention. One is his modified form of Atwood's machine, which I have placed under the heading of falling bodies. This change of order seemed to me to be necessitated by my omitting the words "Old and New" from the title of this article.

His other instrument, which was however his first in the order of time, he calls an isotomeograph, because it shows the law of the constancy of areas by an equality of sectors. Its principle is the same as that of Poinsot's bent spring. In its first shape it consisted of a horizontal trussed beam, nearly 9 meters long, suspended by a wire in the thousand-year-old Leonine tower, which was nine meters in internal diameter with walls four meters thick and without any windows. The beam carried three pairs of basins at different heights, the upper and lower pairs being vertically under the point of suspension, while the middle pair were at the ends of the beam. Metal pipes allowed 160 kg of mercury to run from the upper pair of basins to the middle pair, and from these to the lower ones, the object being the transference of masses from the center of a horizontal and balanced beam to its extremities and the reverse.

In the second form of the apparatus, the mercury was replaced by two equal masses of lead, which were transported on small carriages, running on horizontal rails, from the center of the beam to its ends or vice versa,

by means of two cords and a weight hanging below. The mercury, as well as the lead weights, were set in motion by an electric current which burned out a fuse. All iron and steel were excluded from the construction in order to preclude magnetic disturbances. When the masses were transferred from the ends to the middle, the beam swung towards the left. It swung towards the right when they were moved from the center to the extremities. During the two years 1908-1910, 36 alternate trials were made, and the beam did not even once turn in the wrong direction.

The principle of the isotomeograph is neatly shown by a small rotational energy contrivance, which the writer of the present article lately purchased from a dealer in physical apparatus. It consists of two equal sliding weights at the extremities of a horizontal bar, which is supported at its center and can be turned around a vertical axis with any desirable speed. Cords are attached to the weights in such a way that they may be drawn inward simultaneously towards the axis. When this is done, the weights fly around much faster, but reduce their speed again when the cords are relaxed. The science of mechanics tells us that the moment of momentum of the system, that is to say, the product of the weights, their linear speed and their distance from the center must be constant. As the weights do not vary, it follows that the linear speed and the radius of the circle they describe are reciprocally proportional, each increasing as the other is diminished. Thus, if the radius is reduced one half, the linear speed is twice as great. As the circumference described is now one-half of what it was, the angular speed is four times as great, and the weights swing round four times as often as before. Since the area of the small circle is one-fourth that of the large one, the area swept over by the cord, technically the radius vector, is the same in a unit of time as it was at the start.

The same explanation applies to the isotomeograph. When the beam is apparently in absolute repose, it is in reality, like the tower itself and the ground, turning with the earth in anti-clockwise direction with a speed, which in Rome amounts to about ten degrees an hour, according to Foucault's law. When the weights are near the extremity of the beam, they turned with a certain rotational energy. When they are drawn inward, their angular speed is increased, and the beam must turn faster than it did at the start, faster therefore than the tower and the ground, and must apparently swing to the left or anti-clockwise. When the weights are near the middle of the beam at the start of a new experiment, their outward motion must turn the beam clockwise, since they now lose both linear and angular velocity at the expense of a larger radius.

The result was in perfect accord with the theory, the beam turning $0^\circ.167$ in a minute. It is scarcely necessary to remark that the experi-

~~ments were performed at night, that the room was tightly closed, and that the deflections were observed by means of a mirror upon the circular graduation on the wall.~~

~~Two defects, however, made themselves prominent, one being the want of sufficient precision in noting the position of the centre of gravity of the moving masses, and the other the uncertainty as to whether the rails at both sides of the beam were accurately in the same vertical plane. An improved apparatus is therefore under construction according to Tessan's idea, whose theory, however, is erroneous. The beam will consist of three parallel horizontal bars in the same plane, the outer ones being equal and bolted together, and the middle one having the mass of both of them. These bars will then be simultaneously drawn out or in. They will be made as light as possible and provided with heavy weights at their ends.~~

## TOTAL ECLIPSE OF THE MOON, 1913 MARCH 21.

Dr. EDWARD GRAY.

On the evening of March 21 it was raining in Central California—at least in the Sonoma Valley,— and the prospects for seeing the total eclipse of the moon, due between three and four oclock in the morning (Pacific Standard Time), were very dubious. The rain came however in squalls, not continuously, and this fact afforded some measure of hope. About 2:30 a.m. (22nd) the clouds parted. Just after three o'clock one of the night attendants rang my telephone call and announced that the eclipse was visible and that the stars were out. The latter was true in patches or regions, not generally. I repaired hastily to my telescope house. On the walk thither the eclipse was so thorough that it cost me some trouble to locate the moon and many on night duty were unable to see the eclipse because of want of knowledge where to look for the moon. With the exception of the time it took for a small patch of cloud to pass over the moon I saw the eclipse well between 3:20 and 3:50. After a naked eye reconnoissance I observed first with my binocular field-glass. This showed a delicate crescent of subdued light upon the disappearing limb. Then observation followed through the finder and the telescope itself. All the instruments revealed the dull, coppery hue of the expanse of the moon's disk admirably. On viewing through the telescope I was struck with regret at once that I had not been called a full hour earlier; for there was the visible